DESIGN OF ADAPTATION MEASURES BASED ON THE ASSESSMENT OF CLIMATE CHANGE IMPACTS ON EXTREME FLOODS IN THE ATTANAGALU OYA BASIN, SRI LANKA

JAYATHILAKA Ralapahana Mudalige
Charya Prabodha Sri[*]
MEE22721

Supervisor: Prof. RASMY Mohamed[**]
Prof. KOIKE Toshio[***]
Prof. MUROTA Tetsuo[****]
Dr. TAMAKAWA Katsunori[*****]

ABSTRACT

The Attanagalu Oya Basin experiences frequent flood hazards due to high-intensity rainfall events. Complex flow behavior, rapid infrastructure development, and high population density increase basin exposure, leading to severe damage. The proposed development activities are concentrated on low-lying regions and floodplains, requiring comprehensive basin-wide risk evaluation to assess their potential impact. To address these issues, this study presents a comprehensive approach for evaluating future rainfall variations to determine flood exposure and probable risk by employing bias-corrected climate-projected outputs from general circulation models (GCMs) and simulating the rainfall-runoff-inundation (RRI) model. These results indicate an increase in future extreme and long-duration rain events. The hydrological model results imply that inundation will increase, thereby increasing flood vulnerability. The findings emphasize that the flood-exposed population could increase from 13.8–22.5% and building exposure from 9.8–20% in the study area owing to climate change. The proposed risk matrix and land-use zoning are valuable for risk-based land-use planning, regulating urbanization in flood-prone areas and promoting resilient building practices. This study provides evidence-based information for policymaking, community awareness, and future flood exposure reduction, laying the groundwork for end-to-end approach to climate change adaptation.

Keywords: Climate change, RRI model, Inundation, Risk matrix, Urbanization

INTRODUCTION

The Attanagalu Oya Basin is one of the major river basins in the wet zone of Sri Lanka, and a large portion of it is located in the highly populated Western Province. The well-known Katunayake International Airport is located in this basin, along with major cities such as Gampaha, Ja Ela, and Negombo. The basin features flat terrain, a meandering river network, and an interconnected stream system. Figure 1 shows a map of the Attanagalu Oya Basin. The average annual rainfall is 2685 mm, contributing to an annual water yield of 1129 MCM, with 845 MCM discharged into Negombo Lagoon. The basin had a population of 1.6 million in 2012, with a high population density of 2000 people/km^2, projected to reach 2.9 million by 2040 (Population and Housing Census, 2012). Owing to its high population density and complex flow behavior, the basin is vulnerable to flooding, which has occurred several times in recent years,

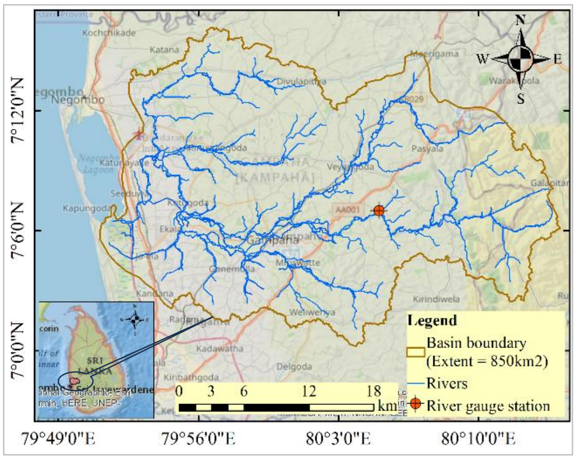


Figure 1. Study area (Attanagalu Oya Basin)

---

[*] Civil Engineer, Sri Lanka Land Development Corporation

[**] Adjunct Professor GRIPS/ Senior Researcher, ICHARM

[***] Adjunct Professor GRIPS/ Executive Director of ICHARM

[****] Professor GRIPS/ Director of Disaster Risk Management Concentration

[*****] Research Specialist, PWRI, ICHARM

with severe floods occurring in 2006, 2007, 2010, 2012, 2016, 2018, and 2021. Flood damage has increased owing to a lack of information regarding flood inundation and hazard risks in the basin. Many developments have been proposed for floodplains, some of which are currently ongoing. These factors must be reviewed while incorporating climate change.

Previous studies have not addressed climate change impact, as they were based on current climatology. Additionally, these studies did not assess the basin's future land development impact concerning flood risk (Perera et al., 2012). Owing to climate change impact on precipitation, extreme events are expected to increase in magnitude and frequency, leading to severe floods and heightened basin vulnerability. Therefore, there is a need for evidence-based information on future climate projections and their impact on extreme floods to evaluate future probabilistic risk. This information is vital for sound policymaking regarding risk-based land-use management, aiming to regulate urbanization activities and reduce future exposure to basin floods.

This study utilizes the climate-projected bias-corrected outputs of the general circulation model (GCM) and rainfall–runoff–inundation (RRI) model to assess the potential impact of floods under present and future climatic conditions. The ultimate objective is to develop a risk-based land-use policy framework to facilitate the effective regulation of future development in the basin.

THEORY AND METHODOLOGY

The methodology adopted in this study consists of four components, as shown in the flow chart (Figure 2).

a.) Climate change analysis

Climate change analysis involves two main components: past climatology study and future projected climatology analysis. Past recorded rainfall data from ground gauging stations were used to analyze historical rainfall trends. For future climatology, GCMs were employed to project data for the period 2050–2075, and bias-corrected GCM data were obtained from the CMIP-5 archive in the DIAS. The GCM selection was based on comparing key meteorological variables with global reanalysis products in specific regional and local domains. A three-step statistical bias correction was applied to correct the bias of GCM data using observed rainfall data (Nyunt et al.,2016). Future climatological analyses involved innovative trend analysis, extreme rainfall variation examination, and change comparison during long-spell rainfall events.

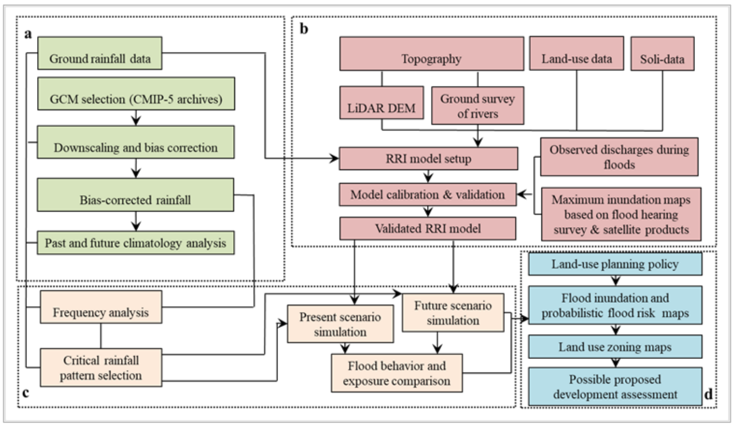


Figure 2. Methodology flow chart.

b.) RRI modeling

A basin-scale RRI model was developed to assess the hydrological response of the basin to past and future climatic conditions. The model theory is based on the mass balance and momentum equation for gradually varying unsteady flows in two Cartesian directions. RRI employs the diffusion wave approximation, neglecting the inertia terms in the momentum equations (Sayama, 2022). The model was calibrated and validated using the 2021, 2018, and 2016 extreme events. The model performance was evaluated using the Nash–Sutcliffe efficiency (NSE), mean bias error (MBE), and root mean square error (RMSE) for discharge comparison at the river gauging station, while inundation extent was compared using the measure of fit criteria.

c.) Flood behavior, exposure and frequency analysis

The most extreme event in the last 10 years was compared with future expected events projected by applying the incremental factors obtained from the GCM-projected annual rainfall maxima to the same, where pessimistic average and optimistic factors were chosen. Changes in inundation extent, depth variation, population exposure, and buildings were compared between the past and future climatic scenarios. To obtain past and future rainfall intensities corresponding to 5-, 10-, 25-, 50, and 100-year return periods, a basin-critical 4-day historical in situ and bias-corrected rainfall series from the GCMs were fitted to the Gumbel distribution. Rainfall pattern analysis was performed to distribute return period rainfall intensities according to past critical rainfall patterns. All policies and findings proposed in this study are based on a pessimistic scenario, representing the most adverse future conditions. Therefore, the frequency analysis focused on comparing the inundation depth and extent variation for different return periods under past and future pessimistic conditions.

d.) Risk-based land-use planning and policy framework

Finally, a risk-based land-use planning and policy framework is proposed to regulate future urbanization activities and assess proposed and ongoing development work impact. A risk matrix was developed based on flood occurrence probability and damage level potential magnitude (Ichidate et al., 2016). Based on the risk matrix, cumulative probabilistic flood-risk maps were created for the basin to represent the spatial risk distribution. Considering the inundation depth, occurrence probability, expected damage level, and country development strategy, two land-use zones (future urbanization restricted and flood risk) were identified to regulate flood exposure.

DATA

Daily rainfall data from five gauging stations (1980–2020) were obtained from the Meteorological Department. Hourly rain and river discharge data for extreme events were obtained from the Meteorological and Irrigation Departments. The LiDAR digital elevation model (DEM) and ground survey data from the river network were used to create the RRI river and slope inputs. Building footprint data were downloaded from the Microsoft Global Building Footprint Database, and population data were acquired from the Department of Census and Statistics.

RESULTS AND DISCUSSION

a.) Climate change analysis

The innovative analysis examined past rainfall trends in the basin using historical in-situ rainfall events from 1980–2020, as shown in Figure 3. No discernible trend is demonstrated in low-intensity rainfall. However, rainfall exceeding 150 mm/day has shown an increasing tendency in the recent past (2001–2020) compared with that of the distant past (1980–2000).

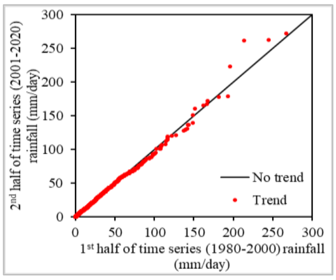


Figure 3. Past trend.

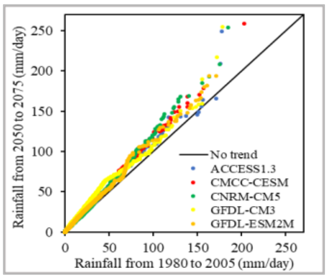


Figure 4. Future trends.

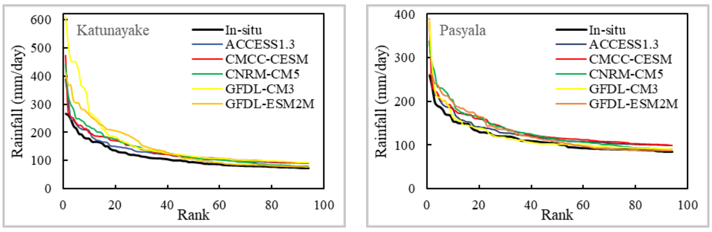


Figure 5. Future extreme rainfall.

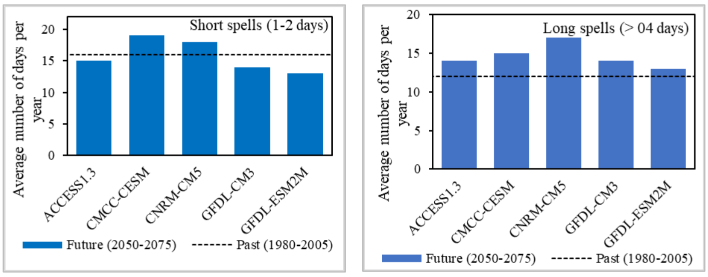


Figure 6. Rainfall event variation.

The basin average rainfall was considered for future rainfall innovative trend analysis, and the different GCM relevant trends are shown in Figure 4. All the models showed an increasing trend in intensities above 100 mm/day. The ACCESS1.3 model indicates a minor increasing trend in intensity ranging from 150–175 mm/day.

Significant increases in future extreme precipitation were observed across all models upstream (Pasyala station) and downstream (Katunayake station) of the basin, as shown in Figure 5.

Rainfall event analysis was conducted by considering rainy days as precipitation > 1 mm/day, and the results are shown in Figure 6. Three models indicated a decrease and two showed an increase in future short-duration rainfall events (< 2 days). However, for long-duration rainfall events of > 4 days, all models projected a future increase, with a 21.7% increase in the average number of days per year compared to that in the past. This variation emphasizes that a greater number of long-duration rainfall events can be expected in future.

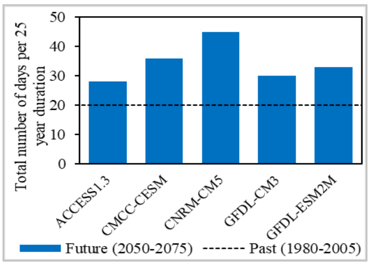


Figure 7. Occurrence of extremes.

A comparison of the projected future extreme rainfall event occurrence (intensity of more than 100 mm/day) is shown in Figure 7. All models indicated an increase in the occurrence of extremes, with a 72% average increment compared to past conditions. These results provide strong evidence of an increase in extreme rainfall events across both magnitude and frequency, indicating that the basin may experience more floods in the future than it has in the past.

b.) RRI model calibration and validation

The RRI model was calibrated for extreme events occurring between May and June 2021. The calibration results showed good agreement between the observed and simulated discharge at the river gauging station, with goodness of fit indices of NSE = 0.7, MBE = -8.61 m^3/s, and RMSE = 20.0 m^3/s.

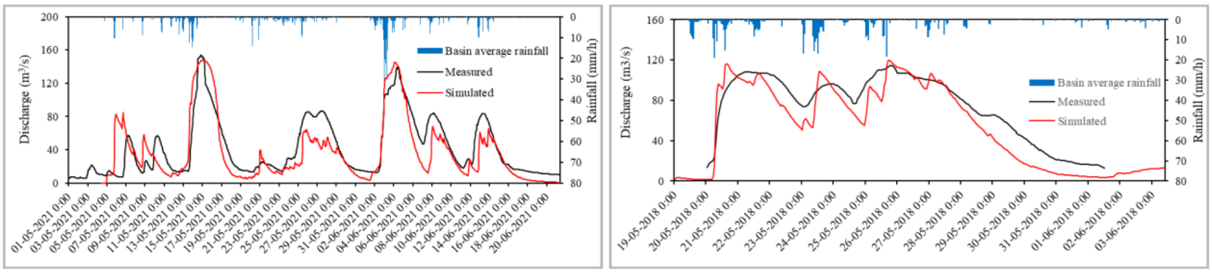


Figure 8. Observed and simulated discharge at river gauge (Left – calibration, Right – validation).

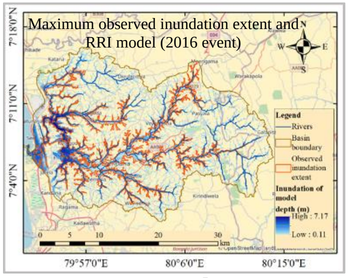


Figure 9. Inundation extent.

Two extreme events were selected for validation. Comparing the discharge for the extreme event in May 2018 resulted in an NSE of 0.75, whereas inundation extent assessment for the extreme event in May 2016 resulted in a measure of fit value of 67.3%, indicating reasonable agreement between the observed and model-provided flood extents. The corresponding hydrographs and inundation extent maps are shown in Figures 8 and 9, respectively.

c.) Flood behavior, basin exposure, return period intensities and inundation

Incremental factors in annual maxima of selected GCM projected rainfall compared to those of the past and considered factors for pessimistic, average, and optimistic scenarios are summarized in Table 1. The May–June 2021 extreme event was found to be the most critical past event, and it was used for basin flood behavior and exposure comparison with future climatic scenarios (Table 2).

Table 1. Annual maxima factors.

GCM /Climatic scenario	Factor
CMCC-CESM	1.05
CNRM-CM5	1.35
GFDL-CM3	1.37
GFDL-ESM2M	1.01
Pessimistic	**1.37**
Optimistic	**1.01**
Average	**1.20**

Table 2. Discharge and inundation comparison

Scenario	Inundation extent (km^2)	Inundation as % of the basin area	Increment factor compared to the 2021		
			Inundation extent	Flood volume	Peak discharge
Optimistic	135	15.9	1.07	1.05	1.04
Average	166	19.5	1.32	1.22	1.15
Pessimistic	202	23.8	1.60	1.47	1.39

Notably, the increase in inundation extent was more significant than the increases in flood volume and peak discharge.

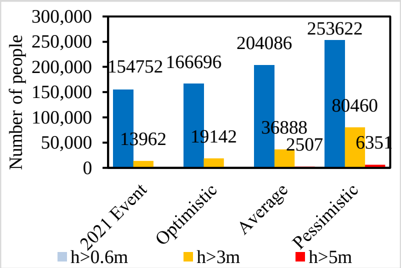


Figure 10. Population exposure.

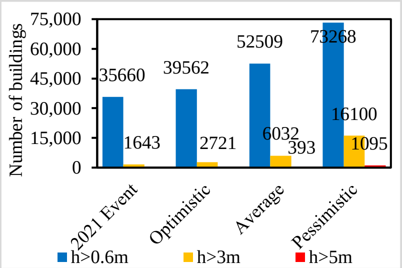


Figure 11 Building exposure.

Flood exposure was evaluated by assessing affected populations and buildings (Figures 10 and 11). The estimated percentages of the flood-affected population and buildings due to the 2021 event were 13.8% and 9.8%, respectively, which can increase to 22.5% and 20% under pessimistic scenarios. These facts highlight the future flood vulnerability of the basin and the importance of reducing flood exposure by incorporating the land-use policy and enhancing community awareness of flood disasters.

The four-day rainfall duration was selected for the frequency analysis because it represents the basin's critical rainfall duration. Table 3 summarizes the rainfall intensities for different return periods, considering the past and future Thiessen average rainfall series from the selected GCMs. The increasing (pessimistic) factors were consistent across all return periods, and were applied to represent the climate change impact on future rainfall at each gauging station. The inundation depth variation and inundation increment compared with those of past conditions for the 10-, 50-, and 100-year return periods are shown in Figure 12.

Table 3. Return period and factors of future climatic scenarios.

GCM/ Climatic scenario	10-year return period			50-year return period			100-year return period		
	Past (mm/4-day)	Future (mm/4-day)	Factor	Past (mm/4-day)	Future (mm/4-day)	Factor	Past (mm/4-day)	Future (mm/4-day)	Factor
CMCC-CESM	355.5	397.7	1.12	467.4	519.0	1.11	514.7	570.2	1.11
CNRM-CM5	310.4	392.9	1.27	401.5	518.4	1.29	440.0	571.5	1.30
GFDL-CM3	337.7	425.0	1.26	431.1	576.1	1.34	470.6	639.9	1.36
GFDL-ESM2M	377.0	410.7	1.09	496.3	529.2	1.07	546.7	579.2	1.06
Pessimistic			**1.27**			**1.34**			**1.36**

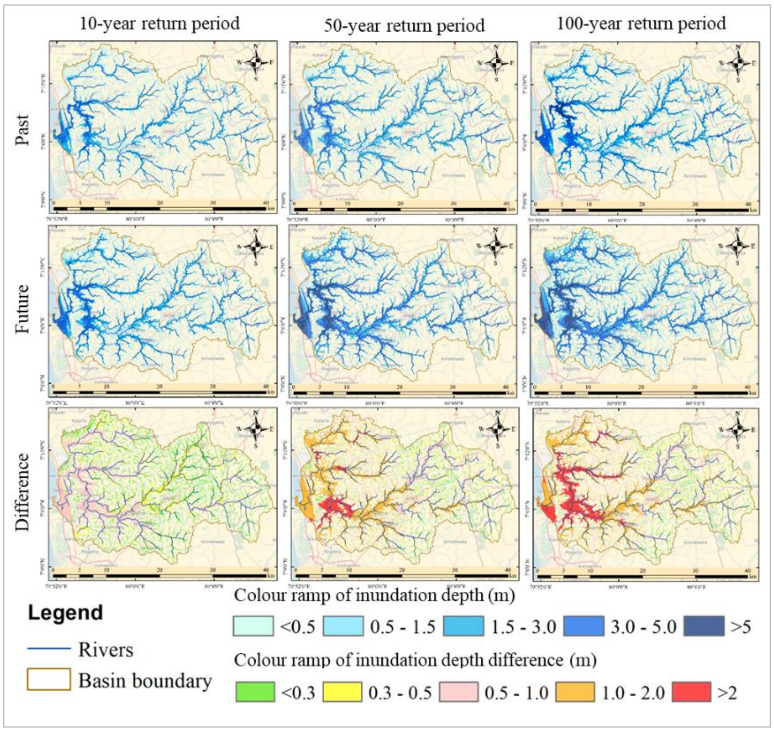
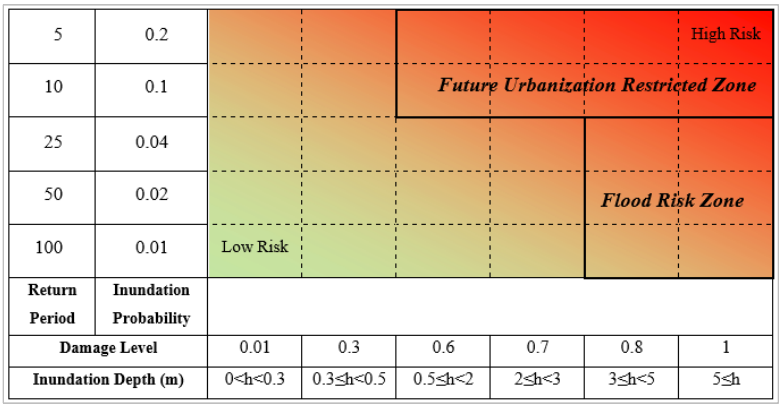


Figure 12. Return period inundation depth variation.

d.) Risk-based land-use planning and policy framework

The safety level against flooding is proposed to be determined using a risk matrix, which involves an assessment of the probability of flood occurrences and the potential magnitude of damage they may cause. The proposed risk matrix for the study area is shown in Figure 13.

A risk matrix was employed to provide a comprehensive visualization of the varying levels of probabilistic cumulative flood risk in the study area, as shown in Figure 14. This study emphasizes that an increase in flood risk is expected in the future, even in areas with no flood risk under the current conditions.



5	0.2						High Risk
10	0.1			Future Urbanization Restricted Zone			
25	0.04						
50	0.02					Flood Risk Zone	
100	0.01	Low Risk					
Return Period	**Inundation Probability**						
Damage Level		0.01	0.3	0.6	0.7	0.8	1
Inundation Depth (m)		0<h<0.3	0.3≤h<0.5	0.5≤h<2	2≤h<3	3≤h<5	5≤h

Figure 13. Risk matrix and proposed land-use regulation.

The future urbanization-restricted zone is defined as an area in which the expected inundation is > 0.5 m over a 10-year return period. Future urbanization activities will not be allowed in this zone. A flood risk zone was categorized as an area in which the expected inundation is > 3 m over a 100-year return period. Development work is subject to building regulations and current residents will be promoted to build safe evacuation spaces above the estimated inundation level. These two zones are illustrated in Figure 15.

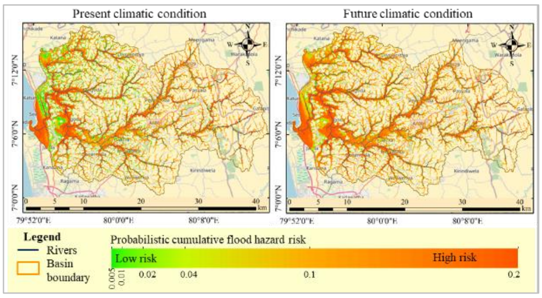


Figure 14. Probabilistic cumulative flood risk.

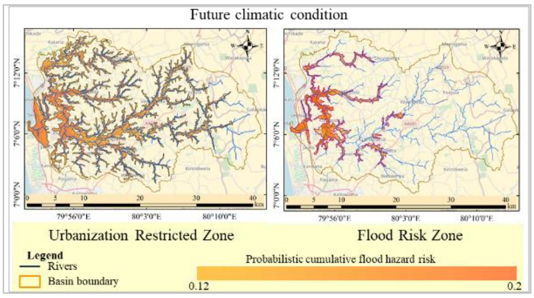


Figure 15. Proposed land use zones.

The study indicated that the urbanization-restricted area would increase by 32.4% owing to climate change, leading to the inclusion of 55,000 more people and 15,800 additional buildings in that zone. In addition, the ongoing central expressway project involving road embankment construction in low-lying areas was assessed for induced probable flood risk. The findings indicated that road embankment construction converted 0.5 km^2 into an urbanization-restricted zone, and climate change impact increased by 44%, exposing 600 buildings at risk.

CONCLUSIONS AND RECOMMENDATIONS

This study employed evidence-based information to formulate a risk-based land-use policy framework to address future potential flood impact. Climatological analysis revealed that all the selected GCMs projected an increase in high-intensity rainfall events in the basin. Future event RRI simulations indicated a significant increase in flood volume, peak discharge, and inundation extent. These findings emphasize that the basin will experience future climate change impact through high-intensity, long-duration rainfall events, frequently leading to more severe floods. Risk assessment indicated that the future flood-affected population is projected to rise from 13.8–22.5%, building exposure from 9.8–20%, and flood risks are expected to rise, even in areas previously considered safe from floods. Therefore, it is essential to incorporate risk-based land-use policies to restrict urbanization in flood-prone areas and promote resilient building practices.

The pressure and release model conceptualizes the flood disaster risk reduction framework through a vulnerability analysis based on the study findings. The proposed risk matrix and land-use zoning are recommended for implementation in risk-based land-use planning. The current practice of development possibility assessment involves limited catchment assessment focusing on specific areas, whereas this study enables a holistic approach by conducting a basin-wide probabilistic risk evaluation. This study lays the foundation for a pathway towards climate change adaptation by emphasizing the need for an end-to-end approach that integrates scientific, engineering, and socioeconomic approaches.

ACKNOWLEDGEMENTS

I express my profound gratitude to my supervisor, Professor Mohamed Rasmy, for continuous support, instruction, and encouragement throughout the research. I am grateful to Professor Toshio Koike for his patient guidance, valuable advice, and support during my studies. Special thanks are also extended to Dr. Katsunori Tamakawa for his guidance and technical support during this study.

REFERENCES

Ichidate, S., Tsuji, M., Taki, K. and Nakamura, H. (2016). The Risk-Based Floodplain Regulation of Shiga Prefecture in Japan. E3S Web of Conferences, 7, p.13008.

Nyunt, C.T., Koike, T. and Yamamoto, A. (2016). Statistical bias correction for climate change impact on the basin scale precipitation in Sri Lanka, Philippines, Japan and Tunisia. Hydrology and Earth System Sciences Discussions.

Perera, K.R.J. and Wijesekera, N.T.S. (2012). Potential on the Use of GIS Watershed Modeling for River Basin Planning - Case Study of Attanagalu Oya Basin, Sri Lanka. Engineer: Journal of the Institution of Engineers, Sri Lanka, 45(4), p.13.

Sayama, T. (2022). Rainfall-runoff-inundation (RRI) Model Technical Manual. International Center for Water Hazard Risk Management, PWRI.